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09/16/02

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OTHER AUTHORS
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KEYWORDS FOR INDEXING *(Separate terms with commas)*
gravity gradiometer, cold atoms, polarization spectroscopy

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Our section manager is [redacted] J. Zumberge

Thank you very much.

Nan Yu

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Gravity measurements using polarization spectroscopy

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Light-pulse atom interferometry has been successfully used for sensitive gravity measurements, in which electromagnetic waves are used to manipulate cold atoms through the interaction with atomic internal states and any resulting changes in atomic state are measured through probing the atomic state population. We propose here an alternative approach to gravity measurement using cold atoms by a direct phase readout of the electromagnetic waves. We show theoretically that the sensitivity of such a measurement is comparable to that of light-pulse atom interferometer. Aside from being a different scheme, the new approach offers the possibility of a single phase measurement to recover the gravity gradient when employing two spatially separated atomic ensembles. In addition, the technique may also be used for nondestructive optical detection of ultracold atoms in atomic interferometers.

In this paper, we will focus on the properties of polarization rotation gravity gradiometer. A possible configuration of experimental setup is shown in Fig. (1). A linearly polarized wave is decomposed into two linearly (horizontally and vertically) polarized light waves with the same power via a polarizing beam splitter (PBS) that is rotated at 45° with respect to the incoming light polarization. The linearly polarized light waves are transformed into circularly polarized waves via $\lambda/4$ wave plates placed after the beam splitter. After the interaction with the atomic beam the waves propagate through the same $\lambda/4$ plates and become linearly polarized waves emerging the system through the second port of the beam splitter.

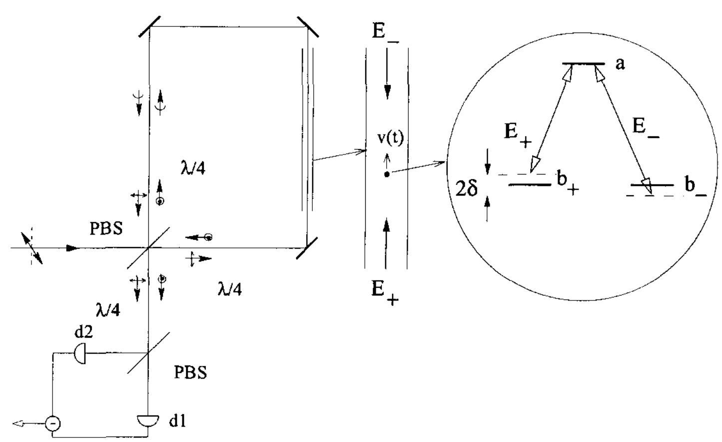

Figure 1 – Measurement scheme. A three-level atom interacts with two counterpropagating waves having the opposite circular polarizations. The atomic motion results in detuning of the fields from the corresponding atomic transitions in atom's frame of reference. This detuning results in change of the index of refraction for the waves that may be measured in the interferometric scheme.

Let us consider a Λ-type energy level scheme (Fig. 1) interacting with two resonant counterpropagating light waves with electric fields E_+ and E_-. Corresponding Rabi frequencies for the fields are $\Omega_\pm = \wp_\pm E_\pm/\hbar$, where $\wp_\pm$ are the dipole moments of the corresponding atomic transitions. For the sake of simplicity we assume that they are equal. The population radiative decay $2\gamma_r$ of the exited level $|a\rangle$ is given by the expression $\gamma_r = 4\omega^3\wp^2/(3\hbar c^3)$.

The information about atomic velocity is stored into the relative phase shift of the light waves. To measure it we can first send the beam through another $\lambda/4$ plate rotated at 45^o with respect to the both polarizations as in a polarization analyzer arrangement. The polarization rotation as well as light power can be measured by the two photodetectors $d1$ and $d2$ at the second PBS exiting ports. The signals from these photodiodes are proportional to $(1/2)(I_+ + I_- \pm 2\sqrt{I_+ I_-} \sin\ 2\phi)$, where I_+ and I_- are the powers of the circularly polarized components of the field. Therefore, the sum of the photocurrents gives us the total output power, and the difference of the photocurrents gives the polarization rotation angle.

The Hamiltonian that describes the behavior of atomic internal degrees of freedom is

$$H_a = \frac{\hbar k}{m}(P(0) - mgt)(\hat{\sigma}_{b+b+} - \hat{\sigma}_{b-b-}) + \hbar\left(\Delta - \frac{\hbar k^2}{2m}\right)\hat{\sigma}_{aa} - \hbar(\Omega_+\hat{\sigma}_{b+a} + \Omega_-\hat{\sigma}_{b-a} + adj.) \quad (1)$$

where $\hat{\sigma}_{ij} = |i\rangle\langle j|$ are the atomic operators, k is a wave vector for the electromagnetic wave, m is a mass of the atom, Δ is the single photon detuning of the carrier wave frequency on the frequency of the corresponding atomic transition. The initial generalized momentum of the atom is

$$P(0) = mv(0) - \frac{\hbar\omega_0}{c}(\hat{\sigma}_{b+b+}(0) - \hat{\sigma}_{b-b-}(0)). \quad (2)$$

To derive Eq. (1) we have used the normalization condition $\hat{\sigma}_{b+b+} + \hat{\sigma}_{b-b-} + \hat{\sigma}_{aa} = 1$. Eq. (1) is valid if changes of atomic parameters due to atomic motion in the gravity field occur adiabatically. This condition can be met by constantly sweeping the frequencies of two circularly polarized waves to track the major Doppler frequency shift.

In the polarization measurement scheme we detect photons, not atoms. It might seem that increase of the photon number leads to increase of the measurement sensitivity. However, it turns out, that the optimization of the system with respect to the atomic absorption results in optimum photon number n approximately equal to the number of atoms in the cloud $\mathcal{N}$ and, therefore, is very small. The maximum measurement sensitivity is determined by signal to noise ratio

$$\left(\frac{S}{N}\right)_{max} = \xi\frac{\pi g T^2}{\lambda}\sqrt{\mathcal{N}}, \quad (3)$$

where ξ is a parameter of the order of unity, T is the measurement time, g is the constant acceleration we would like to detect, λ is the wavelength of the electromagnetic wave. Ratio (3) nearly coincides with the maximum signal to noise ratio for conventional gravity gradiometers based on the atomic interferometry. Note, however, that the atomic projection noise was not explicitly used in deriving (3).

The measurement described here is a Quantum Nondemolition Measurement with respect to the generalized atomic momentum P. The measurement scheme may give a precise information about initial velocity $v(0)$ of atoms without changing it if the final population of atomic levels is the same as the initial level population. If the atoms were initially prepared in $|b_+\rangle$ state the generalized momentum is determined by the initial atomic velocity and by a constant value of photon recoil momentum $P = mv(0) - \hbar k$, $(\hat{\sigma}_{b+b+}(0) = 1)$. This initial value of the momentum stays unchanged in time if there is no acts of spontaneous emission. The measurements are interesting because they allow one, in principle, to violate energy-time uncertainty relation and make a measurement of energy of the atomic cloud with uncertainty $\Delta\mathcal{E}$ less than $\hbar/T$.

Reaching the maximum sensitivity in a real experiment might be difficult in the continuous regime of the probe laser operation because of the small photon number needed. One solution is to initially prepare the atomic ensemble in the dark state with a strong pulse followed by a continuous non-absorptive probing with the required weak probing intensity. The second solution is to operate in a pulsed mode, similar to the light-pulse interferometer. In this case, one needs to measure redistribution of the photon numbers in the light pulses (motion induced ellipticity) instead of the polarization rotation. It is possible then to utilize coupling optical pulses that are used in conventional atomic interferometry for retrieving information about number of atoms participating in the interaction as well as about interferometer's signal itself.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.